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The phenology and seed production of *Cucumis melo* as an invasive weed in northern Iran

Sima Sohrabi[A,C], *Javid Gherekhloo*[B], *Behnam Kamkar*[B], *Ali Ghanbari*[A] *and Mohammad Hassan Rashed Mohassel*[A]

[A]Faculty of Agriculture, Ferdowsi University of Mashhad, PO Box 91775–1163, Iran.
[B]Gorgan University of Agricultural Sciences and Natural Resources, PO Box 49189–43464, Iran.
[C]Corresponding author. Email: simsoh@gmail.com

Abstract. Accurately representing plant development is essential for applying phenology knowledgement to investigate the effects of climate on weed management. Development in wild melon (*Cucumis melo* L.) is driven by temperature; thus, it could be simulated by thermal-time (TT) accumulation using limited accumulation when a lower optimum temperature (T_{opt}) is exceeded. Experiments were conducted to investigate wild melon phenology (development rate) and seed production in soybean (*Glycine max* L.) at seven different sowing dates (April to August) in a completely randomised design (CRD) at Research Farm of Gorgan University of Agricultural Sciences and Natural Resources, Iran, during 2012. Results indicated that a slight shift in developmental rates occurs among plantings dates, except for those plants sown in August. The estimated TT for April–August planting dates were ~411 Celcius degree days, 448 Celcius degree days, 733 Celcius degree days, 672 Celcius degree days, 604 Celcius degree days, 558 Celcius degree days and 251 Celcius degree days respectively. Depending on planting date, weed emergence occurred at 5–20 days after planting. During the 79, 75, 92, 81, 71, 67 and 61 days of wild-melon growth, the mean number of fruits per plant and seeds per fruit were significantly different at each sowing date. Wild melon could produce a lot of fruits and seeds (up to 5000) within a growth cycle (average in 75 days) and also weed management is needed during the May and June because of the highest seed production of wild melons that emerged during May. The results attained here suggest that temperature alone could not reflect the effect of environment on *C. melo* development at each given growth stage. Thus, other environmental factors, such as daylength, maybe needed to better estimate weed development. Future research may use multiplicative models to clarify this claim. These results highlighted the value of testing a model over a wide range of environments.

Additional keywords: *Cucumis melo* subsp. *agrestis* var. *agrestis*, growth cycle, thermal time, weed management, wild melon.

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Introduction

Cucumis melo is a monoecious, annual, trailing-vine plant of the Cucurbitaceae family. The reproduction of *C. melo* takes place only by seeds. The inedible fruits are berries of spherical to ovoid shape, with a very thin mesocarp and many tiny seeds (Dje *et al*. 2006; Kouonon *et al*. 2009). There are four species of the Cucurbitaceae family that are invasive weeds in Australia, China and America (Tingle and Chandler 2003; Wang *et al.* 2009; Shaik *et al.* 2012). *Cucumis melo* is native to Asia but is aggressively invading crop lands in northern Iran and many parts of North America. It infests crops such as cotton (*Gossypium hirsutum* L; Prostko and Chandler 1998; Tingle and Chandler 2003), peanuts (*Arachis hypogaea* L.; Grichar 2007*a*) and soybean (*Glycine max* L.; Grichar 2007*b*; Sohrabikertabad *et al*. 2013).

Invasion is the geographical expansion of a species into an area not previously occupied by that species (Vermeij 1996). Invasive weeds can be non-indigenous and indigenous species that can become overly abundant in a plant community (Booth *et al*. 2003). Biological processes and characteristics that are most important for weeds to thrive are dependent on reproduction, dispersal and phenology, among others (Bryson and Carter 2004).

Phenology is observing periodically recurring phenomena of plant growth and recording the time of their occurrence (Schwartz 2003). The timing of emergence, growth and sexual reproduction is highly important for success of invasive weeds. The phenology of a weed is mediated by the interaction of internal factors with external environmental signals such as temperature, daylength or drought (Godoy *et al*. 2009; Dincer *et al*. 2010). Therefore, understanding the factors that control phenological variability is crucial for the design of durable weed-management practices (Dincer *et al*. 2010). Properly timed control tactics reduce the cost of managing weeds and decrease the potential for yield reductions from increased weed competition or crop injury (Forcella 1993).

Mechanistic models that describe environmental effects on distinct processes involved in emergence, i.e. seed dormancy, alleviation, imbibition, germination and seedling elongation, have provided a useful approach for predicting weed phenology (Forcella *et al*. 2000). For example, Roman *et al.* (2000) developed a model for predicting common lambsquarters (*Chenopodium album* L.) emergence that uses hydrothermal time to describe germination and thermal time to describe shoot elongation. One practical approach to weed-emergence simulation is hydrothermal model, which accumulates units of hydrothermal time from soil temperature, when soil water potential is above a base value (Archer *et al*. 2001). The forecast of weed emergence in potato production increased tuber yield and improved weed management (Felix *et al.* 2009). *Cucumis melo* was used in our study because it is frequently found in Golestan province especially in soybean *(Glycine max* L. Merr) and can cause significant crop yield losses. The flexibility for seed germination in the late growing season and under adverse environmental conditions may aid *C. melo* in evading control tactics that are usually employed during crop establishment (Sohrabikertabad *et al*. 2013). There is limited knowledge regarding the thermal-time requirements for *C. melo* growth and reproduction. Checking phenological behaviour of this plant species along with its seed production would be useful for decision-support systems helping managers select the best management strategies and, thereby, improving *C. melo* control. Also, the phenology data would allow predicting *C. melo* invasibility of new areas. The present study was aimed to determine whether thermal time concept is enough to quantify the phenological behaviour of this weed. Also, investigating the seed production of wild melon in different planting dates will be considered.

Materials and methods

Study site

The experiment was conducted during 2012 growing season at the Research Farm of Gorgan University of Agricultural Sciences and Natural Resources, Iran (36°85′N, 54°27′E), with annual rainfall of 607 mm per year. The soil type was loamy, with 18% sand, 46% silt, 36% clay and 1% organic matter and a soil-water pH of 7.6. The field experiment was managed without pesticides or fertilisers.

Experimental design

To expedite field operations, a randomised plot design with six replicates was used to test phenological characteristics and seed production of wild melon. Seeds of wild melon were collected from a soybean field located in Golestan province in northern Iran during August 2011. After harvest, the seeds were bulked, cleaned manually, placed in a paper bag and stored at room temperature. Seed dormancy was not detected prior and after storage. Seed viability was 97% according to a tetrazolium chloride test (ISTA 2009). Seeds were planted in three rows spaced 150 cm apart in each plot. Plots were 3 m wide and 4 m long and 20 seeds were sown at a depth of 2–3 cm in the seven sowing dates each, namely on 22 April, 5 May, 23 May, 7 June, 22 June, 11 July and 16 August, to evaluate the influence of varying air temperature on growth and development of wild melon. The sowing dates were selected to have plants develop under contrasting temperatures because they emerge and grow within and out of the recommended sowing dates for this location and soybean production.

The cardinal temperatures were estimated by regression analysis on germination rate (GR), which was calculated as the reciprocal of time to reach cumulative germination percentage of 50% of total germinated seeds (D50), for data collected for wild melon against mean temperature (T). Germination-rate model was fitted using an intersected-lines model (Eqn 1) procedure of SigmaPlot ver. 11, Systat Software Inc., as follows:

$$\begin{aligned} GR &= b \times (T - T_b) \quad \text{if } T \leq T_o \\ GR &= C \times (T_c - T) \quad \text{if } T \leq T, \end{aligned} \tag{1}$$

where T_b, T_o and T_c are considered the base, optimum and ceiling temperatures respectively, and a and b are the regression coefficients. On the basis of the tent-shaped model output (segmented lines model), the base, optimum and maximum (ceiling) temperatures for germination of wild melon were estimated at 20°C, 34.9°C and 44.6°C respectively (Fig. 1).

Method

Phenological characteristics of wild melon plants were studied during the summers of 2011 and 2012. To prevent initial plant mortality, plots were kept as weed free as possible for up to 40 days after emergence by hand-hoeing. Emergence date was the date when 50% of the plants had emerged through the soil surface. When all plants had emerged, plants were thinned to achieve the target plant density (six plants per plot). Seedling emergence was counted twice a week following seed burial so as to calculate cumulative emergence. The field was visited twice a week and, on each occasion, time to 50% seedling establishment, time to emergence, leaf appearance (2-, 4- and-6 leaf appearance), flowering stage (female- and male-flower appearance), fruit set and time to maturing were recorded. Fruit number per vine was recorded and 10 mature fruits of plants at each replication were collected randomly to evaluate seed number per fruit and seed weight in late of August.

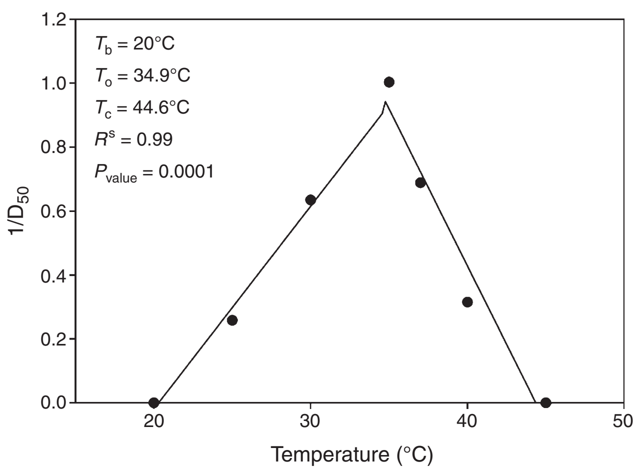

Fig. 1. Intersected lines model fitted to D50 against different constant temperatures for wild melon.

Data analysis

Data were analysed with SAS 9.1 (SAS Institute 2009) to assess the effect of planting date on seed production. The thermal-time (TT) approach was used to predict wild-melon development stages. The daily increment of thermal time was calculated as (Streck *et al*. 2003):

$$\mathrm{DTT} = (T_{\mathrm{o}} - T_{\mathrm{b}})\,.f(\mathrm{T}), \tag{2}$$

where f(T) is the temperature function, T_o is the optimum temperature and T_b is the base temperature. The first component of the daily thermal time ($T_o - T_b$) is constant, and non-optimal temperature will affect daily thermal time through f(T). f(T) is temperature function (as a reduction factor) that varies between 0 (outside the optimal range of temperatures) and 1 (optimal temperature) (Kamkar *et al*. 2012). The base, optimum and ceiling temperatures for *C. melo* are 20°C, 35°C and 45°C respectively (Sohrabikertabad *et al*. 2013). Values of the cardinal temperatures are input as parameters.

Response of this weed to photoperiod is probably day-neutral and vernalisation-free, phenological stages are affected only by temperature. In this model, environmental factors are represented by response functions that range from zero to one. When the temperature-response function is zero, development does not take place and a calendar day has not any role as a physiological day. This is the case when temperature is equal to extreme temperatures or below the minimum or above the maximum temperature. Development takes place at the maximum rate if the response function is one, which occurs when temperature is exactly at optimum.

The integrated TT for each developmental phase was calculated by accumulating DTT. Each phenological stage occurred when integrated DTT reached the TT specific to each stage. For this, in a daily time step, integrated DTT was divided by corresponding required TT, and each step took place as a result of this division to reach the unit. Development rate was calculated by dividing DTT by TT of occurrence of each development stage. Then temperature function and related parameters were arranged in a process-oriented algorithm to predict development rate of wild melon using ModelMaker software ver. 3.0 (Cherwell Scientific Limited 2014). Weather data were uploaded as a lookup file at a daily-step scale.

Results

Daily minimum and maximum air temperatures were recorded in a standard weather station (36°85′N, 54°27′E, 13.3 asl), ~3 km from the field site (Table 1, Fig. 2).

Table 1. Descriptive statistics for minimum, maximum and average temperatures in 2012

		Mean	s.d.	Range	CV
Air temperature	Minimum temperature (°C)	14.16	8.46	30.80	59.74
	Maximum temperature (°C)	24.77	9.38	38.40	37.90
	Average temperature (°C)	19.64	8.70	31.50	44.70
Soil temperature	Minimum temperature (°C)	22.90	4.70	25.20	20.80
	Maximum temperature (°C)	30.91	5.65	25.60	18.28
	Average temperature (°C)	26.90	5.03	25.10	18.69

Emergence

The maximum cumulative emergences were observed after 140 Julian days, after which four distinct emergence flushes were detected at ~160, 170, 190 and 230 Julian days during the growing season of *C. melo* (Fig. 3). This suggests that the start time for *C. melo* management should be near summer and after about 120 Julian days, and should be applied in about four periodical times. *Cucumis melo*, like other annual weeds, is a problem that we face throughout the growing season because it germinates and emerges at different times, allowing it to escape from control operations, produce seed and create soil seed banks that may persist for several years. Plants that emerge first (up to the second flush) are more competitive than are wild melon plants that emerge late (Flushes 6 and 7) because of differences in the competitive ability of crops among different growth stages.

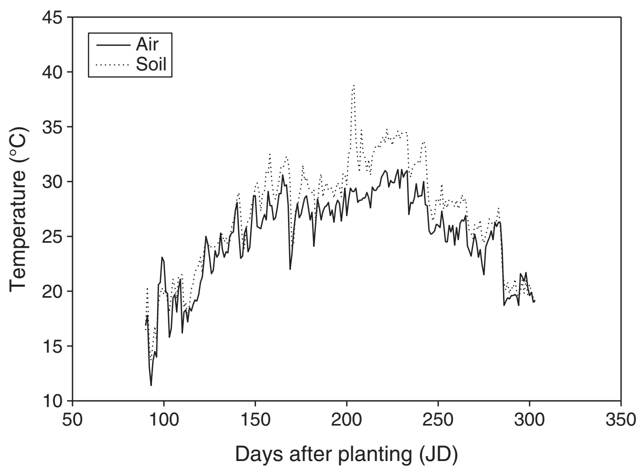

Fig. 2. The temperature variation during the study (from 1 April onward) during 2012.

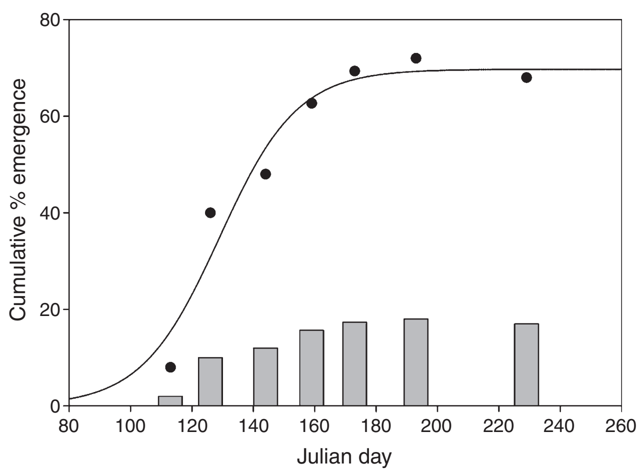

Fig. 3. Cumulative emergence (%) during the growing season. The vertical line above the *x*-axis shows the multiple distinct emergence flushes of *Cucumis melo* during seven sowing dates.

Table 2. The required thermal time for different phenological stages of *C. melo* in different planting dates according to *f* (t)
Data in parentheses is corresponding to Julian date for each stage

Phenological stage	Sowing date						
	22 April (1st)	5 May (2nd)	23 May (3rd)	7 June (4th)	22 June (5th)	11 July (6th)	16 August (7th)
Emergence	41 (136)	55 (141)	54 (154)	107 (173)	84 (186)	83 (204)	46 (249)
2- or 3-leaf appearance	88 (145)	93 (148)	94 (160)	140 (178)	137 (193)	119 (208)	69 (253)
4- or 5-leaf appearance	149 (156)	130 (154)	131 (165)	204 (187)	189 (200)	145 (211)	103 (259)
Branching	177 (160)	169 (160)	173 (173)	249 (193)	220 (204)	264 (224)	125 (263)
Flower appearance	222 (166)	243 (169)	189 (183)	301 (200)	274 (210)	315 (229)	171 (272)
Fruit appearance	281 (174)	317 (180)	338 (193)	333 (204)	324 (216)	414 (239)	200 (280)
Maturity	411 (192)	448 (198)	733 (236)	672 (240)	604 (245)	558 (260)	251 (310)

Development rate

During the growing season of wild melon with different and broad-ranging planting dates, environmental conditions varied drastically. The mean air temperature during of the study was ~26.5°C (Fig. 2). Seeds of wild melon germinated as soon as soil reached optimum temperature. The model estimated that a minimum of 5 days was required for 50% emergence of wild melons on 25 August (the seventh sowing date) that corresponded to the highest temperature during the growing season. The maximum number of days required for wild melon emergence was 20 days, which occurred at the first planting date (22 April) when soil temperatures were the lowest. Seeds that were planted later developed more rapidly than did those planted earlier (Table 2).

Required TT calculated from soil temperature was higher than that estimated from air for emergence of wild melon, but both had the same fluctuations during seven sowing dates (Fig. 4).

The calculated TT for each growth stage is presented in Table 2. Depending on the planting date, the required daily TT was different for each phenological stage. Depending on sowing date, TT requirements were 300–733 Celcius degree days for weed-growth complement of wild melon according to *f*(t). The estimated TT for seven planting dates were 411, 448, 733, 672, 604, 558 and 251 Celcius degree days respectively. We expected a constant or close TT for all sowing dates if the model worked properly; however, it seems that *f*(t) cannot quantify the response of this plant to the environment and other factors such as minor response to daylength, vernalisation requirement or indeterminate growth of this plant may affect the phenological response of the plant (Table 2). The lowest development rate occurred on coldest day (the first and second planting dates) and with the rising air temperature, the development rate of wild melon increased (remaining planting dates). The development rate of weeds that were planted in August had an obvious decrease at the end of growing stage (maturation; Fig. 5).

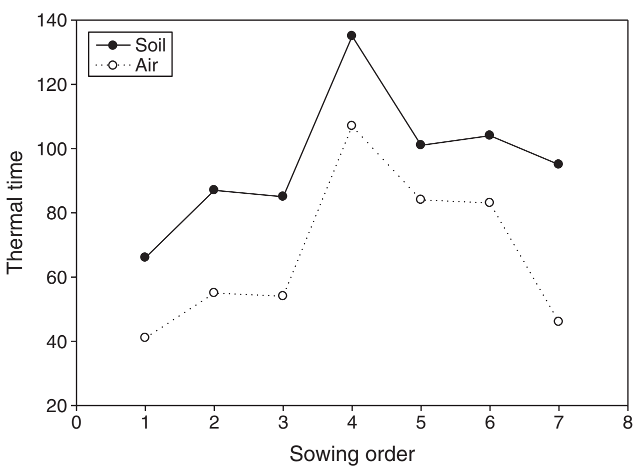

Fig. 4. Thermal time of wild melon emergence according to soil and air temperature at seven sowing dates during 2012.

Seed production

The weed exhibited monoecious tendencies, with production of female flowers rapidly followed by production of male flowers on the same vine. *Cucumis melo* exhibited prolific fruit production, until senescence occurred at 79, 75, 92, 81, 71, 67 and 61 days after establishment for different sowing dates, respectively. The time of 50% fruit formation was observed 61, 49, 54, 45, 42, 46 and 37 days after emergence, depending on the temperature and date of sowing (planting dates from May to August respectively). Therefore, wild melon could produce fruit and seed in less than 2 months (Fig. 3). There was a decline in wild-melon growth and seed production in the latest planting date, because of the short growing season. During different growth-periods lengths (79, 75, 92, 81, 71, 67 and 61 days), the mean number of fruits per plant and seeds per fruit varied significantly among the sowing dates. The lowest and highest fruit and seed numbers per plant were 10.3, 45.33, respectively (fruits per plant), and 458.65, 8606.8, respectively (seeds per plant), and were obtained in August and May respectively. The maximum seed number per vine was 5000, and it differed depending on environmental conditions. The greatest seed weight (0.62 g per 100 seeds) was obtained from plants sown in late May (Table 3). No significant differences were observed in seed weight among different sowing dates from April to August, but there was significant difference between the latest sowing date (August) and the May sowing date. Total seed number per plant varied from 440 to 8505 seeds per vine in different sowing dates.

Discussion

Emergence

Time of seedling emergence determines the ability of a plant to compete with its neighbours, survive against biotic and abiotic stresses, and to reproduce (Forcella *et al.* 2000). Therefore,

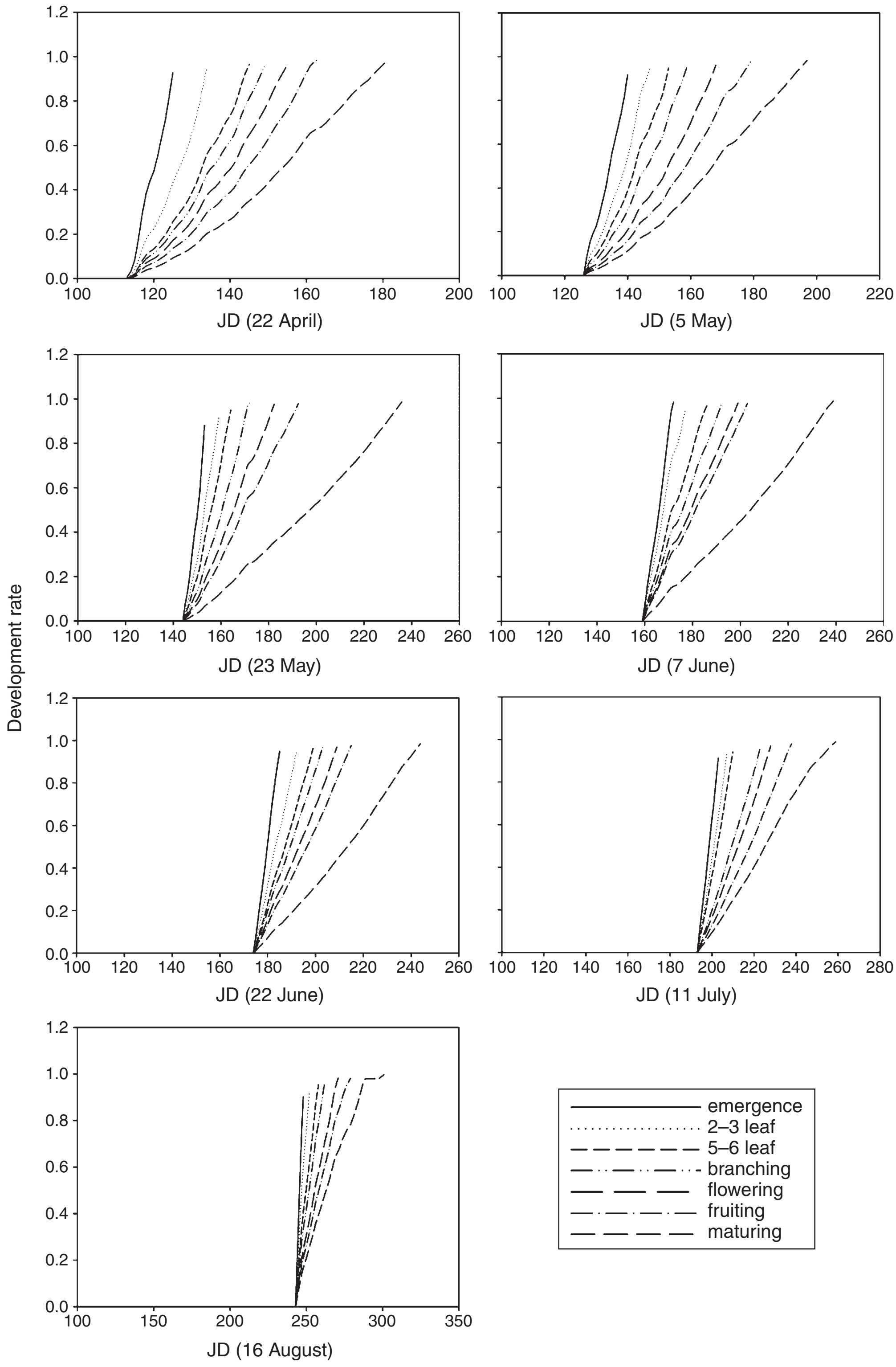

Fig. 5. Development rate of wild melon at seven sowing dates during 2012.

knowledge of the emergence periodicity of weed is important in planning effective weed-control programs, such as herbicide application or non-chemical strategies (Bullied *et al*. 2003). The required minimum time for emergence was different and depends on the weed species, environmental conditions and planting depth (Bekker *et al*. 2003). *Fimbristylis miliacea* seedlings emerged 3 days after planting (Begum *et al*. 2008). More phenological stages (shorter growth-stage intervals)

Table 3. Length of growth period, number of fruits per plant, number of seeds per fruit and seed weigh of wild melon at seven planting dates
Values within a column followed by the same letter are not significantly different at $P = 0.05$

Planting date	Length of growth period (days)	Number of fruits per plant (l.s.d. = 18.19)	Number of seeds per fruit (l.s.d. = 0.29)	Seed weight (g per 100 seeds) (l.s.d. = 0.19)
22 April (1st)	79bc	14.33c	151.07dc	0.53ab
5 May (2nd)	75c	45.33a	189.87a	0.55ab
23 May (3rd)	92a	34.33ab	172.13ab	0.62a
7 June (4th)	81b	26.6bc	155.07abc	0.53ab
22 June (5th)	71cd	18.66bc	188.67bcd	0.57ab
11 July (6th)	67d	13c	137.23d	0.43ab
16 August (7th)	61de	10.3c	44.53d	0.41b

occurred in warmer days (Dincer *et al*. 2010). Different developmental stages of common *Chenopodium album* L., *Echinochloa crus-galli* (L.) P.Beauv., *Amaranthus retroflexus* L. and *Sinapis arvensis* L. varied among different planting dates because of different genetic and genotypic responses to environmental interactions during the growing period (Shrestha and Swanton 2007). An important benchmark for implementation of post-emergence control measures is the time required for emergence of a given percentage of the potential population (Webster *et al*. 1998). Understanding phenological stages and their characteristics is crucial for design of sustainable weed-management practices (Dincer *et al*. 2010).

Development rate

Our results indicated that a slight shift in developmental rates occurs among planting dates, with the exception of seeds planted in August. On the basis of f(t), high developmental rates were observed in cold days (below the T_{opt}; Fig. 5). Development rates for many processes (both phenology and others such as leaf appearance) are decreased when air temperature is above T_{opt}; the response has often been curvilinear under many controlled-environment and some field studies (Cao and Moss 1989; Masle *et al*. 1989*a*, 1989*b*; McMaster *et al*. 2008). Temperature was the main environmental factor that had an effect on the developmental rate of the phenological stage for many plants (McMaster *et al*. 2008; Cave *et al*. 2013). McMaster (2005) reported that maximum and minimum temperatures bracket this average, and much of the diurnal temperature is well within the portion of the response curve where the developmental rate increases linearly with temperature. For the earliest planting dates, relatively cold temperatures at our location limited plant growth, compared with later planting dates when the average monthly temperatures approached 28°C. According to these results, time of emergence, flowering and fruit set of wild melon were different and varied depending on environmental conditions. Therefore, the right time for wild-melon management varies according to the wide range of environmental conditions and probably among different production areas.

Seed production

Kouonon *et al*. (2009) reported that immediately after fruit setting, seeds of wild melon were formed and were capable of germination. Thus, wild melon should be managed before fruit production to reduce its population during the next growing season. Shaik *et al*. (2012) reported that the first fruit formation in prickly paddy melons (*Cucumis myriocarpus*) and camel melons (*Citrullus lanatus*) took place between 35 and 49 days after emergence. The camel melons and prickly melons produced a maximum of 14 and 120 fruits per plant, and 400 and 45 seeds per fruit respectively (Shaik *et al*. 2012). Phenology in general and reproduction in particular are strongly dependent on the length of growing period and the size (Shea *et al*. 2006). Spatial and temporal variation in flowering time is crucial for plants pollinated by animals with specific emergence times or subject to seasonal migration (Bustamante and Búrquez 2008). The numbers of seeds per capitulum and per plant of *Bidens pilosa* L. were greater in the normal-type than in the early type plants (Gurvich *et al*. 2004). The number of seeds produced by a plant is the product of the following four variables: (1) the size of the plant, (2) the proportion of assimilate allocated to seeds, (3) the mean seed weight and (4) the pollinating agent (Kaul and Koul 2008; Kouonon *et al*. 2009; Toorop *et al*. 2012). The seed-production capacity of weeds varies greatly both within and among species. Most annual weeds produce a few thousand seeds per individual when growing with minimal competition, although some produce 10 000–25 000 seeds per plant (Bekker *et al*. 2003). Prolific seed production of introduced weeds enables them to become naturalised plants and further spread into new areas by increasing propagule pressure and, thus, to become invasive (Richardson *et al*. 2000). According to the results of the present study, wild melon can produce many fruits and seeds within a growth cycle (average 75 days) and so it is necessary to perform weed management during May and June, because the wild melons emerging during these months will produce the highest number of fruits and seeds.

Our study showed that wild melon is adapted to warm temperature (up to 25°C) and the phenological development of this weed is influenced by temperature and maybe photoperiod. Vernalisation, is not a key process in the life history of this weed species and it can flower in summer, following germination in late spring. The time requirement for each phenological stage was different and varied depending on soil (emergence phase) and air temperature, and also development rate and seed production of wild melon depended on temperature. The global distribution of an invasive weed could be predicted by using a phenological model coupled with climate models. Thus, growth and development study of a specific invasive weed species is an organising principle for the integration of weed-management practices to reduce the area of infection. The results of the present study could be useful in predicting the area susceptible to *C. melo* invasion and invasion success. Further research is required to determine management strategies that could be used later in the growing season to limit the invasion of *C. melo*, and also to predict growth and phenological development of this weed when it grows in direct competition with other crops. When TT reaches 154–204 Celcius degree days, it is the best time to use management options on *C. melo*. These differences in TT for each sowing date could help construct a basic frame for a variety of weed-management tactics to achieve successful control. It seems that the first 100 Celcius degree days after emergence would be the most appropriate time to control *C. melo* by mechanical methods and using early post-emergence herbicides. According to the results (time of emergence and fruit production), efficiency of operations such as tillage and herbicide application for wild melon management is possible at early stages of wild melon emergence (up to 100 Celcius degree days after emergence). Creation of weather-based emergence models that could be updated daily would be an important step towards optimising both herbicide-intensive and non-chemical weed-control systems. Although we tried to construct a temperature-based model to quantify and identify the phenological schedule of this weed in a simple mathematical algorithm, our results indicated that temperature function alone could not reflect the effect of environmental factors on required TT for each given stage; therefore, it may be affected by other factors such as daylength. This emphasises the necessity of a comprehensive study on the simultaneous responses of this weed to temperature and photoperiod (photothermal concept) by multiplicative non-linear models. This could be performed by exposing this weed to different temperature and daylength regimes in a controlled environment or different sowing dates, with precise recording of phenological stages.

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